

Modelling of Gas Engines Integrated with Organic Rankine Cycle and Rankine Cycle

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Abstract

In this paper the integration of gas engines with combined cooling, heating and power (CCHP) systems was presented. The gas engine model was integrated of Rankine cycle and organic Rankine cycle in Aspen HYSYS V7.3 for potential waste heat recovery and utilization. The effect of exhaust gas temperature at different operating conditions on the efficiency and output power of the system were investigated and compared. The system integration resulted in an increase of 7% and 5% in the overall system efficiency and output power respectively. The system integration offered potential recovery of the waste heat for additional power generation whilst providing cooling and heating demands.

Keywords

Modelling; Gas Engines; Organic Rankine Cycle; Rankine Cycle; Trigeneration

Introduction

The availability of energy sources and global warming are major concerns for the sustainability of future energy production. The demand for energy has been on a steady increase despite the limited availability of fossil fuels (Al-Sulaiman, Hamdullahpur, and Dincer 2011b). For instance, the world energy consumption is expected to rise by about 40% between 2006 and 2030 (Al-Sulaiman, Hamdullahpur, and Dincer 2011b) with an increase of 1.1% per year in residential energy usage (Conti and Holtberg 2011), while a rapid increase in greenhouse gas emission is anticipated and this creates a serious concern of environmental pollution (Gao, Wu, Jin, and Yang 2008, Al-Sulaiman, Hamdullahpur, and Dincer 2011b). Therefore, with steady rise in residential consumption of energy, there is a need to give much attention in devising the most efficient, cost effective and least polluting energy conversion method (Khatri, Sharma, Soni, and Tanwar 2010, Angrisani, Rosato, Roselli, Sasso, and Sibilio 2012, Lai and Hui 2010, Al-Sulaiman, Dincer, and

Hamdullahpur 2010) and promote technologies that reduces the depletion of the ozone layer, greenhouse gas emissions and use of fossil fuels (Bell 2008). With the Kyoto agreement, more emphasis is paid on reducing energy use from fossil fuels and evolving energy efficient systems such as combined cooling, heating and power (CCHP) (Maidment, Tozer, and Missenden 2001).

Combined cooling, heating and power (CCHP) also known as trigeneration has emerged as the solution to reduce overall emissions in domestic and small-scale applications whilst increasing the efficiency of the system. It can simultaneously generate mechanical power (often converted to electricity), heating and cooling from one primary source (Ma, Wang, Yan, Dai, and Lu 2011, Malico, Carvalhinho, and Tenreiro 2009).

Gas engines as prime movers are a proven technology with an extensive range of size and the lowest capital cost of all CCHP systems (Amid, Saffaraval, and Saffar-avval 2010) and also possess good operating reliability, high efficiency at part load performances offering flexibility in fuel types usage (Wu and Wang 2006). The efficiency of conventional power plants based on single prime movers is often less than 39% with most of the energy is lost as waste heat. Integrating the cooling and heating subsystems with conventional power plant can increase the efficiency of the plant to 80% (Al-Sulaiman, Hamdullahpur, and Dincer 2011b). In a trigeneration system, the waste heat from the power production subsystem can be utilized to drive the heating and cooling systems (Al-Sulaiman, Dincer, and Hamdullahpur 2010). This waste heat can also be utilized through absorption refrigeration (Klemeš and Varbanov 2011, Manzela, Hanriot, Cabezas-Gómez, and Sodré 2010) and bottoming cycles such as Rankine cycle (RC), organic Rankine cycle (ORC) and Kalina cycle (KC) to increase

the overall efficiency by recovering waste heat from CCHP systems (Feng, Gao, Qin, and Xie 2010, Ringler, Seifert, Guyotot, and Hübner 2009, Ogriseck 2009).

Waste heat recovery from CCHP systems offers an effective way of utilizing the energy of fuel efficiently, economically, reliably and with less harmful effects on the environment whilst improvement of the overall efficiency of the plant (Kavvadias, Tosios, and Maroulis 2010, Lai and Hui 2009, Al-Sulaiman, Dincer, and Hamdullahpur 2010, Angrisani, Rosato, Roselli, Sasso, and Sibilio 2012).

In this study, the potential of heat integration of gas engines with Rankine cycle and organic Rankine cycle was exploited to improve the efficiency of the system and also exploit waste recovery of gas engines for additional power generation.

Modelling Method

The gas engine model configuration was developed and validated using the Dresser Waukesha gas engine 16V275GL+ specification as reported by Ekwonu (2012). Rankine cycle (RC) model was developed in Aspen HYSYS as reported in literature (Feng, Gao, Qin, and Xie 2010, Katsanos, Hountalas, and Pariotis 2012, Liu et al.) and organic Rankine cycle (ORC) model (Al-Sulaiman, Hamdullahpur, and Dincer 2011a, Kalina 2011, Saleh, Koglbauer, Wendland, and Fischer 2007, Ahmadi, Dincer, and Rosen 2011, Vaja and Gambarotta 2010, Aphornratana and Sriveerakul 2010). Al-Sulaiman et al (2011a) suggested that a typical working fluid for ORC that operate at a high temperature are efficient for ORC. n-octane was selected as working fluid.

1) Gas Engine with Rankine Cycle

The Rankine cycle (RC) with water as the working fluid was integrated with the gas engine exhaust to exploit additional power generation. The model was operated at full load with exhaust gas temperature of 436.2°C. Table 1 shows the input data for the simulation.

TABLE 1 INPUT DATA FOR RANKINE CYCLE AND ORGANIC RANKINE CYCLE SIMULATION

Parameter	Values
Turbine inlet pressure	2000kPa
Evaporator outlet vapour fraction	1.000
Outlet pressure of expander	36kPa
Outlet pressure of condenser	36kPa
Pump outlet pressure	2000kPa

The Rankine cycle was modelled as a closed loop in Aspen HYSYS simulation and the loss of water was not taken into consideration (Fig 1). The closed loop was achieved by using the Recycle operator in Aspen HYSYS, thereby fixing the operating conditions. In Fig. 1, the fuel used in the gas engine subsystem represented by the T-block was natural gas as in the base case simulation of the gas engine. The efficiency of the Rankine cycle calculated using the Eqn. (1):

$$\text{Cycle efficiency} = \frac{\text{Net Power output}}{\text{Heat input}} \quad (1)$$

The overall efficiency of the gas engine integrated with the Rankine cycle was calculated using Eqn. (2) based on literature (Muñoz de Escalona, Sánchez, Chacartegui, and Sánchez 2012), given as:

$$\text{Overall efficiency} = \frac{\dot{W}_{ENG} + \dot{W}_{RC}}{H_{in}} \quad (2)$$

Where

$\dot{W}_{ENG}$ is power generated from the gas engine

$\dot{W}_{RC}$ is the power generated from the Rankine cycle

The gas engine power was calculated using Eqn. (3) while the cycle power was calculated using Eqn. (4):

$$\text{Net Power output} = \text{Power}_{\text{expander}} - (W_{\text{turbchargers}} - W_{\text{compressor}}) \quad (3)$$

$$\dot{W} = \dot{W}_{\text{expander}} - \dot{W}_{\text{pump}} \quad (4)$$

$\dot{W}_{\text{expander}}$ is the expander power and $\dot{W}_{\text{pump}}$ is the power generated from pump

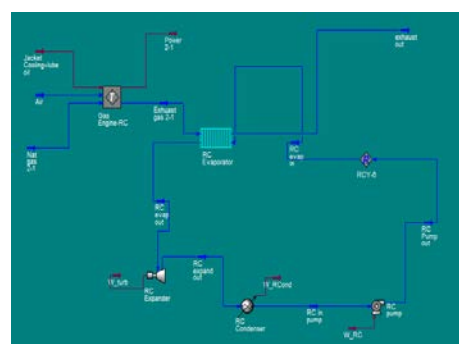


FIG 1: SCHEMATIC OF GAS ENGINE WITH RANKINE CYCLE IN ASPEN HYSYS

2) Gas engine with Organic Rankine Cycle

The organic Rankine cycle (ORC) model in Aspen HYSYS was simulated using the same input data shown in Table 1 so as to have basis for comparison with the Rankine cycle model. In the organic Rankine cycle model, n-octane was adopted as the

working fluid as suggested by Al-Sulaiman et al. (2011a) since it has a high critical temperature. It was assumed that the gas engine operates at full load with the exhaust gas temperature of 436.2°C for the base case integration with the ORC.

The effect of varying exhaust gas temperature of the gas engine integrated with the ORC was investigated. Also, the effect of the evaporator pressure on the system was considered.

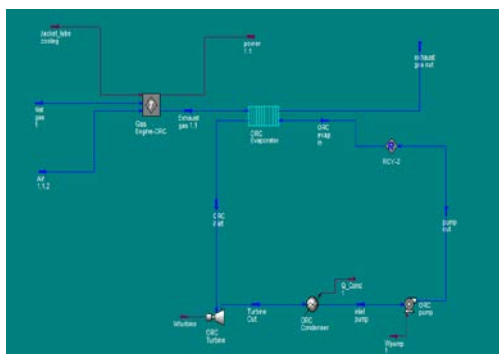


FIG. 2: ASPEN HYSYS MODEL OF GAS ENGINE WITH ORGANIC RANKINE CYCLE

Results and Discussion

Effect of Exhaust Gas Temperature on System Efficiency

The performance of the gas engine with Rankine cycle was investigated using the model in Aspen HYSYS. The exhaust gas temperature and evaporator pressure was varied to evaluate the performance of the system. The minimum evaporator pressure was set to 1000kPa, the critical pressure of water and the maximum pressure was set to 2500kPa, the critical pressure of n-octane, while the exhaust temperature ranged from 290-430°C. The inlet temperature to the expander was defined in order to maintain a minimum approach of 10°C.

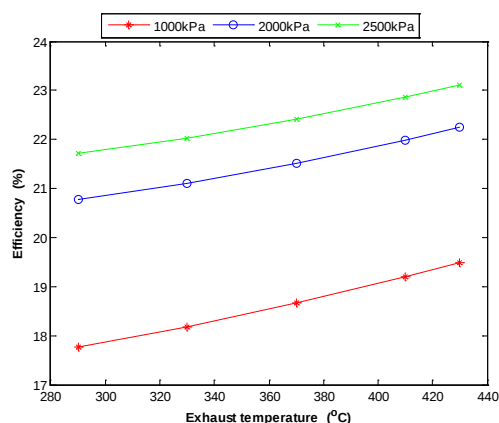


FIG. 3 VARIATION OF RANKINE CYCLE EFFICIENCY WITH EXHAUST GAS TEMPERATURE

Fig. 3 shows the efficiency of the Rankine cycle with the exhaust gas temperature at evaporator pressure of 1000, 2000 and 2500kPa respectively. It can be seen that the efficiency increases with increase in the exhaust gas temperature (increase in turbine inlet temperature), while the efficiency of the organic Rankine cycle decreases with increase in the exhaust gas temperature (Fig. 4). Hung et al. (1997) observed the same trend for water and organic as working fluids and attributed it to the slopes of the isobaric curves in the superheated region of the temperature-entropy diagram. According to Hung et al. (1997) increasing the turbine inlet temperature with ORC using dry, isentropic fluids like n-octane will superheat the working fluid thereby decreases the efficiency of the system. Therefore for ORC system, the turbine inlet temperature should be kept as low as possible preferably above the boiling point of the working fluid as the efficiency of the system is increased.

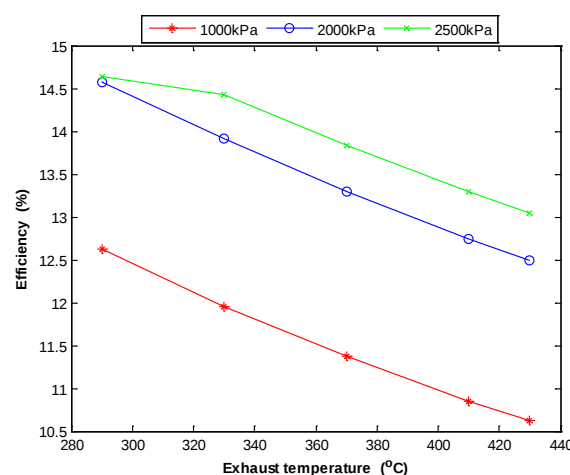


FIG. 4 VARIATION OF ORGANIC RANKINE CYCLE EFFICIENCY WITH EXHAUST GAS TEMPERATURE

Effect of Exhaust Gas Temperature on Power Output

The comparison between the power generated Rankine cycle and organic Rankine cycle at evaporator pressure of 2000kPa is shown in Fig. 5. It can be seen that the Rankine cycle power output increases with increase in the exhaust gas temperature as well as the organic Rankine cycle power output. At exhaust temperature of 420°C, the power generated by the Rankine cycle was 44% higher that generated by the organic Rankine cycle. Although, the Rankine cycle gave higher power outputs compared to the organic Rankine cycle but the organic Rankine cycle is preferred because the working fluid is dry and isentropic overcoming the problems associated with wets fluids (for example, water) (Srinivasan, Mago,

and Krishnan 2010) and the turbine built for ORC is simpler and more economical in terms of capital cost and maintenance cost.

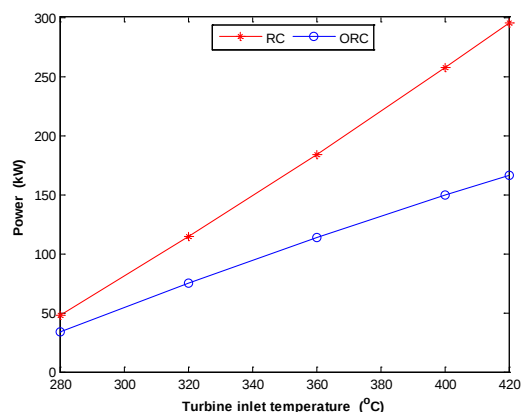


FIG. 5 VARIATION OF RANKINE CYCLE AND ORGANIC RANKINE CYCLE POWER WITH EXHAUST GAS TEMPERATURE AT 2000KPa

Conclusions

The performance of Rankine cycle and organic Rankine cycle integrated with the gas engine was dependent on the type of working fluid used and turbine inlet temperature.

The system performance of the Rankine cycle and organic Rankine cycle with the gas engine offers potential benefit of additional power generated from the recovery of the engine waste heat and also providing heating and cooling demands.

Although the system integration with Rankine cycle gave a higher output power when compared with the organic Rankine cycle but the organic Rankine cycle is preferred due to the nature of its working fluid (dry and isentropic) thereby overcoming problems associated with wet fluid like water. More so, the turbine design for organic rankine cycle is more simpler and economical considering the capital and maintenance cost respectively.

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